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First use of the ^{137}Cs technique in Nigeria for estimating medium-term soil redistribution rates on cultivated farmland

B. Junge [a,1,*], L. Mabit [b], G. Dercon [b], D.E. Walling [c], R. Abaidoo [a], D. Chikoye [a], K. Stahr [d]

[a] International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria
[b] Soil and Water Management and Crop Nutrition Subprogramme, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Department of Nuclear Sciences and Applications, International Atomic Energy Agency (IAEA), 1400 Vienna, Austria
[c] School of Geography, University of Exeter, Exeter, Devon EX4 4RJ, UK
[d] Institute of Soil Science and Land Evaluation, University of Hohenheim, 70593 Stuttgart, Germany

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ABSTRACT

Soil erosion is a serious problem in the forest-savanna transition zone or derived savanna of West Africa and Nigeria and needs to be reduced to maintain soil quality and to ensure food security. In 2007, the use of the fallout radionuclide ^{137}Cs as a tracer for estimating the magnitude of medium-term (40–50 years) rates of soil redistribution was tested at a research station in Ibadan, Nigeria, to investigate, for the first time, its applicability in the derived savanna of West Africa.

Because of the traditional tillage practice for cassava cultivation of creating downslope oriented ridges and furrows during the annual ploughing, there was a need to adapt the ^{137}Cs approach to these specific condition. The mean inventory was determined for cores collected from both ridges and furrows at different positions down the slope and this value was used to estimate the downslope variation in the longer term soil redistribution rate. The mean ^{137}Cs reference inventory obtained for an undisturbed site was 568 ± 138 Bq m^{-2}. The average inventory for the upper slope of the cassava field (423 ± 323 Bq m^{-2}) was generally lower than the average inventory for the middle slope (509 ± 166 Bq m^{-2}) and for the lower slope (606 ± 245 Bq m^{-2}) and these results provided clear evidence of the downslope movement of soil. The mean ^{137}Cs inventory for the study area within the cassava field (496 ± 273 Bq m^{-2}) was 13% lower than the reference inventory, indicating that some of the soil mobilised and redistributed by erosion had been exported beyond the field.

Using ^{137}Cs data set and the conversion model mass balance model 2 (MBM2), the gross erosion rate from the cultivated site was estimated to be 18.3 t ha^{-1} year^{-1} and the net erosion rate 14.4 t ha^{-1} year^{-1}, providing a sediment delivery ratio of 78%. These estimates are comparable to the rates generated by conventional soil loss measurements made close to the study site. The study demonstrates that the ^{137}Cs technique can be successfully used to obtain data on medium-term soil redistribution in the derived savanna of Nigeria, and that it could be a useful tool for supporting the improvement of soil conservation on farmland in West Africa.

1. Introduction

Soil degradation induced by human activity is widespread in Nigeria: its severity is low for 38% of the area (342,917 km^2), moderate for 4% (39,440 km^2), but high to very high for 54% of the area (495,662 km^2) (FAO AGL, 2005). Soil erosion, the most common form of soil degradation in the country, has already become a serious problem. In 1989, about 75% of the southern part of Nigeria was already seriously affected by runoff-induced soil loss and in the north about 25% of the land was degraded, mainly by wind erosion. Sheet erosion is the dominant water-based erosion process in the country, whereas rill and gully erosion are more common in the eastern Nigeria and along the rivers in northern Nigeria (Igbozurike et al., 1989). Erosion induces on-site degradation of the soil resource, resulting in reduced fertility and productivity (Verity and Anderson, 1990). In view of the importance of the soil resource for producing food for the rapidly growing population and its limited availability and resilience (Lal, 1995), there is an urgent need for improved land management to reduce further soil loss.

To understand better the soil degradation problem and to develop effective management strategies, reliable quantitative data on soil loss and redistribution under both traditional and

* Corresponding author.
E-mail address: birte.junge@uni-oldenburg.de (B. Junge).
[1] Now Carl von Ossietzky University, 26129 Oldenburg, Germany.

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novel land management practices are needed (Walling et al., 1999). In Nigeria, various investigations on soil loss have been undertaken using erosion plots, for example, by Lal (1976) in the South West, Odunze (2002) in the North. However, the use of such plots is commonly time-consuming, labour-intensive, expensive, and characterized by a large potential for problems and errors (FAO, 1993). Equations and models to determine soil loss, such as the Universal Soil Loss Equation (USLE) and Soil Loss Estimation Model for Southern Africa (SLEMSA), have been used in Nigeria, for example, by Igwe (1999). However, the lack of direct field measurements means that it is difficult to validate and calibrate these models, and the results obtained are often uncertain.

The use of fallout radionuclides as tracers for soil redistribution by erosion provides an alternative approach to document rates and patterns of soil redistribution and overcomes many of the problems associated with conventional methodologies (Mabit et al., 2008). Caesium-137 (^{137}Cs) is a man-made fallout radionuclide with a half-life of 30.2 years, which was released by nuclear weapon tests that began in the mid-1950s. During those tests, ^{137}Cs was injected into the stratosphere, distributed globally and transferred to the ground as fallout by dry or wet deposition. After the Nuclear Test Ban Treaty of 1963 the fallout decreased rapidly and the main period of fallout extended from the late 1950s through to the early 1970s (Cambray et al., 1989). ^{137}Cs is a useful tracer for investigating soil redistribution because it is quickly and strongly adsorbed by fine soil particles after deposition (Ritchie and McHenry, 1990) and its subsequent redistribution reflects the physical processes associated with water and wind erosion and tillage operations (Govers et al., 1999). The approach can provide information on both erosion and deposition rates and therefore permits the estimation of gross erosion, net erosion, and sediment delivery. Another important advantage includes the potential for estimating soil redistribution rates from entire fields or landscape units which will provide more realistic information than that obtained by attempting to extrapolate measurements obtained from small bounded runoff plots. In addition, the approach is retrospective since it can provide information on medium-term average soil redistribution rates representative of the past 40–50 years and reflect changes in land management. As the sampling only requires a single site visit, the disturbance of the study area is minimal. The relatively simple sampling procedure makes the radionuclide technique cost-effective and less time-consuming than other conventional approaches (Mabit et al., 2008).

The fallout radionuclide approach has been increasingly used to investigate soil redistribution all over the world under various agro-ecological conditions (Zapata, 2002; Mabit et al., 2008). On the African continent, investigations have been reported, for example, from locations in Southern Africa (Collins et al., 2001; Foster et al., 2007), Western Africa (Antwi, 2006), and Northern Africa (Bouhlassa et al., 2000). However, to date comparable investigations involving the use of fallout radionuclides to estimate soil loss have not been undertaken in the forest-savanna transition zone of West Africa, an important fragile agro-ecosystem known for its high population density and extreme soil erosion.

The objective of the study was to test the applicability of the fallout radionuclide approach, and more particularly the use of ^{137}Cs measurements, for documenting for the fist time soil redistribution rates in a cassava field in the derived savanna of West Africa (Nigeria).

2. Materials and methods

2.1. Site description

The study site was located on the research farm of the International Institute of Tropical Agriculture (IITA) in Ibadan, approximately 150 km north of Lagos, Nigeria (Fig. 1A). The forest-savanna transition zone or derived savanna is characterised by a subhumid climate. The rainfall regime is bimodal, with a long rainy season extending from April to July and a short season from September to October/November. The average annual temperature is 27 °C (1986–2007) and the average annual precipitation on the research farm is 1282 mm (1986–2007) (IITA, 2008). The intensity and erosivity of the rainfall in Ibadan are high since 55% of the total rainfall amount falls at intensities exceeding 25 mm h^{-1} and 15% of the total rainfall amount exceeded 75 mm h^{-1} between 1977 and 1999 (Salako, 2006). The mean annual kinetic energy of the rainfall within this period was 213 ± 64 MJ ha^{-1} and the erosivity 9.42 MJ mm ha^{-1} h^{-1} (Salako, 2008).

The landscape of the study area comprises an eroded pediment, and is characterized by a gently undulating relief with slope gradients up to 15°. It is underlain by metamorphic rocks of the Pre-Cambrian Basement Complex, which include banded gneiss, quartzites, quartz schists, and granitic gneisses (Moormann et al., 1975). The soils developed from this parent material are characterized by a sandy loamy topsoil (up to 60% sand) above a gravelly layer

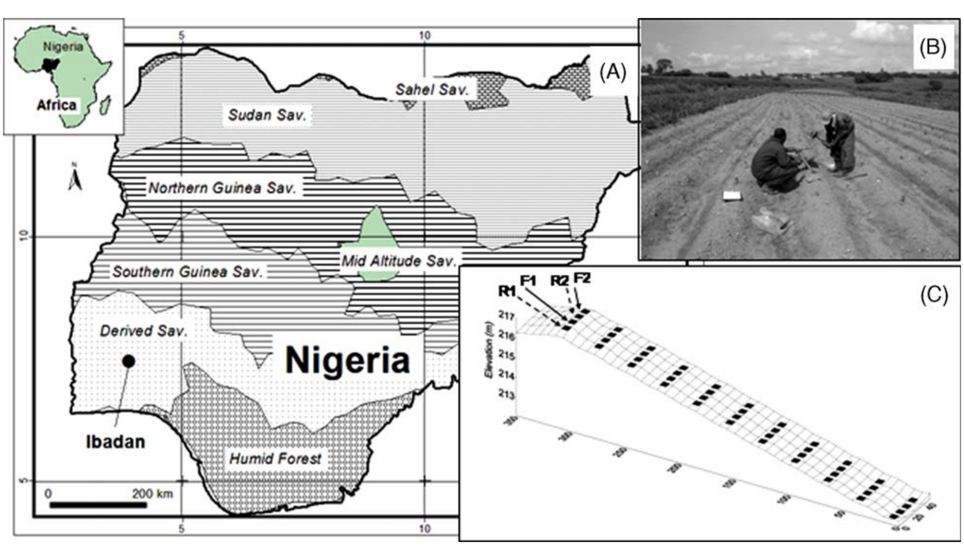

Fig. 1. Location of the study area in Ibadan, Nigeria (West Africa) (A), cultivated site with ridges and furrows and staff taking samples (July 2007) (B), topography of the sloped cultivated site and location of the sampling points (C) (R: Ridge; F: Furrow).

(up to 40% gravel) and clayey subsoil (up to 60% clay) (Table 1). The fertility of the soils is generally low, in the forests and especially on the fields used for decades (topsoil: $C_{org} < 2\%$, $N_t < 0.2\%$, $P_t < 20$ ppm, $K < 0.5$ cmol$_c$ kg^{-1}). According to the World Reference Base for Soil Resources (WRB), the soils of the study area can be classified as ferric Luvisols with the development of an argic horizon in the subsoil with increased clay content, base saturation and cation exchange capacity (IUSS, 2006).

An area of secondary forest (10 ha), that had not been disturbed for about 50 years, was selected as a reference site (7°48′N 3°88′E, 215 m above sea level), since it was not possible to find a suitable area of grassland near Ibadan, which had not been cultivated over the last 40–50 years. The forest included species, such as *Pterocarpus* ssp., *Chlorophora excelsa*, *Albizia zygia*, *Deinbollia pinnata*, *Oxanthus gracilis*, and *Motandra guineensis*. The reference site itself (100 m × 100 m) was situated within a flat part of this forest where no evidence of soil erosion or deposition was observed. The cultivated study site (7°50′N 3°89′E) was located within a field with a slope gradient of up to 6°. The study field (1.75 ha) had been conventionally tilled by regular annual ploughing and/or harrowing down the slope to an average depth of 30 cm, since 1970. The tillage system employed in the field involves the creation of ridges and furrows (Fig. 1B) during the annual ploughing, and planting the cassava crop (*Manihot esculenta*) on the ridges. The ridges and furrows are destroyed and recreated each year and this results in complete mixing of the plough layer on a regular basis. The study field has been mainly used for growing cassava since 1970, and this has only been interrupted by short periods with natural fallows or cultivation of velvet beans (*Mucuna pruriens*) to restore the soil fertility.

2.2. Soil sampling and ^{137}Cs determination

To document the ^{137}Cs inventories within the reference site and the study field, soil samples were collected using a cylindrical metal core tube (length 70 cm, internal diameter 11.8 cm) in July 2007. Twelve core samples were taken randomly to determine the ^{137}Cs activity level and its spatial variability within the reference site. The cores from this site were collected to a depth of 30 cm, since the presence of dense roots and a coarse gravelly layer within the subsoil prevented the collection of cores to greater depths.

Because of the practice of creating ridges and furrows during the tillage operation, there was a need to modify the standard approach for using ^{137}Cs measurements to estimate soil redistribution rates at the study site. To distinguish the longer term soil redistribution associated with water erosion from the short-term and temporary soil redistribution associated with the creation of the ridges and furrows, sets of four samples were collected from both the ridges (2) and furrows (2) at regular intervals downslope (Fig. 1C). The distance between each sampling point along the same ridge/furrow was 30 m, and the distance between the neighbouring transects was 10 m. The cores were collected to a depth of 60 cm to ensure inclusion of the full inventory of ^{137}Cs. In total 44 bulk core samples were collected from the cropland. The resulting inventory values were averaged across the slope to estimate the ^{137}Cs inventory at that position on the slope. This value, rather than the ^{137}Cs inventories associated with the individual cores, was used to estimate the soil redistribution rate at that position on the slope.

In order to provide information on the vertical distribution of ^{137}Cs within the soil of both the reference site and the cultivated field, additional cores were collected and sectioned into 5 cm depth increments. Three sampling points were randomly selected (max. depth 30 cm) within the reference site for collection of sectioned cores and eight sectioned cores were collected from the top and bottom ends of the slope (max. depth 60 cm) in the cultivated site. To investigate the relationship between particle

Table 1
Description of the main physical and chemical properties of the soils in the study sites (Hor. = horizon, Rock = rock fragments, exAc = exchangeable acidity, ECEC = effective cation exchange capacity, < = less than, – = up to) (The properties were analysed as follows: texture (wet sieving, pipette method), pH (electrode), C_{org} (Heanes, 1984), N_t (Bremmer and Mulvaney, 1982), P_t (Bray and Kurtz, 1945), exchangeable bases K^+, Ca^{2+}, Mg^{2+}, Na^+, (Mehlich, 1984), exAc (Anderson and Ingram, 1993)).

Site	Hor.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Rock (%)	pH (H_2O)	C_{org} (%)	N_t (%)	P_t (ppm)	Ca (cmol$_c$ kg^{-1})	Mg (cmol$_c$ kg^{-1})	K (cmol$_c$ kg^{-1})	Na (cmol$_c$ kg^{-1})	exAc (cmol$_c$ kg^{-1})	ECEC (cmol$_c$ kg^{-1})
Uncultivated	Ah1	0–13	68	12	20	<1	5.8	1.52	0.16	8.39	4.69	1.06	0.16	0.21	0.08	6.2
	Ah2	14–29	60	10	30	<5	5.5	0.67	0.07	1.45	1.90	0.90	0.11	0.22	0.17	3.3
	2 Bt1	30–50	52	8	40	–40	5.0	0.49	0.04	0.50	1.68	0.89	0.12	0.20	0.08	3.0
	3 Ct1	51–79	34	10	56	–10	4.7	0.46	0.04	0.05	2.36	1.26	0.07	0.19	0.25	4.1
	3 Ct2	80–100	30	10	60	<2	4.8	0.38	0.03	0.01	2.62	1.25	0.06	0.20	0.33	4.5
Cultivated	Ap	0–23	68	12	20	–30	6.2	0.12	0.03	16.21	3.43	1.20	0.41	0.22	0.17	5.4
	2 Bt	24–34	41	11	48	–40	5.0	0.42	0.11	1.53	1.84	0.65	0.41	0.23	0.25	3.4
	2 Bc	35–52	20	44	36	–30	5.3	0.36	0.04	0.50	2.38	0.87	0.21	0.21	0.25	3.9
	3 Ct	53–100	22	24	54	<2	5.4	0.29	0.03	0.24	2.50	0.77	0.12	0.26	0.17	3.8

size and ^{137}Cs content, topsoil and surface sediment deposits from different slope positions were also collected.

All core samples were air-dried, disaggregated, passed through a 2-mm sieve, and ground. The topsoil and sediment samples were air-dried and separated into different textural fractions (<2, 2–20, 20–53, 53–100, 100–250, 250–500, 500–1000, 1000–2000 μm) by wet sieving and use of the pipette method. The ^{137}Cs content of the <2-mm fraction of each sample was measured by gamma spectrometry in Germany at the Institute for Physics and Meteorology, University of Hohenheim, using a high-purity coaxial germanium detector with a relative efficiency of 48.9% and a resolution (FWHM) at 1.33 MeV of 1.74 keV.

^{137}Cs activities determined from the gamma-spectrum at 662 keV were adjusted to a common date of July 9, 2007. Each measurement took 8–24 h to provide a measurement precision of ±15% at the 95% confidence level with a minimum detectable activity of 0.26 Bq kg^{-1}. The ^{137}Cs mass activities (Bq kg^{-1}) measured were converted into areal activities (Bq m^{-2}) using the bulk density of each soil core. Additional ^{137}Cs released into the atmosphere by nuclear accidents – e.g. Chernobyl in 1986 – was not significant in the study area (WHO, 1986). As indicated above, to take account of the influence of the annual construction of the temporary ridges and furrows on the inventories measured for the individual cores, the average inventory for the cores taken from the ridges and furrows at the same slope position was determined.

The cross-slope averaged ^{137}Cs inventories (Bq m^{-2}) obtained from the cultivated site were converted into quantitative estimates of soil loss or deposition (t ha^{-1}) by using the Improved Mass Balance Model 2 (MBM2) (Walling et al., 2002). This model considers the temporal variation of the annual fallout ^{137}Cs input and the initial distribution of the nuclide before its incorporation into the soil profile by tillage.

For applying this conversion model, the following parameters and default values were used: particle size factor: 1 (default value), proportional factor: 1 (default value), reference inventory: 568 Bq m^{-2}, relaxation depth: 4 kg m^{-2} (default value), sampling year: 2007, tillage depth: 360 kg m^{-2}, year of initial tillage: 1970.

To establish the consistency of the resulting estimates of soil redistribution rates obtained for the cultivated field, these were compared with equivalent estimates of erosion rates obtained by Lal (1976, 1983, 1995) and Kirchhof and Salako (2000).

3. Results and discussion

3.1. Vertical distribution of ^{137}Cs

The depth distribution profiles of ^{137}Cs from the study site are shown in Fig. 2. The three profiles from the reference site are similar (A, B and C). The peak ^{137}Cs concentration of about 5–6 Bq kg^{-1} was located in the 5–10 cm depth increment. Below this depth, the ^{137}Cs activity in the soil declines rapidly. This shape with the subsurface peak reflects both the fallout source of the radionuclide and thus its delivery to the soil surface, slow post-fallout downward migration, as well as the cessation of significant ^{137}Cs fallout, and thus surface replenishment of fallout inputs, in the early 1970s.

Further information on the eight ^{137}Cs depth distributions documented for the cultivated study field is provided in Fig. 2(D–K). The vertical distribution of ^{137}Cs in the ridges (D and E) and furrows (F and G) of the upper slope was almost uniform in the top 30 cm, due to the mixing associated with annual tillage operation (Walling et al., 1999). However, the greater depth of soil containing ^{137}Cs associated with the constructed ridges and the reduced depth of soil containing ^{137}Cs found in the furrows is clearly evident. The depth distributions of ^{137}Cs documented at the bottom of the slope (i.e. H–K) provided evidence of the occurrence of ^{137}Cs to greater depths than at the top of the slope. This reflects the progressive accumulation of soil containing ^{137}Cs at the bottom of the slope. Furthermore, there is greater variation amongst these four depth distributions than for the four depth distributions from the top of the slope. One ridge (H) was characterized by the occurrence of ^{137}Cs to a depth of 60 cm, with maximum activities occurring between 40 and 50 cm. In contrast, the ^{137}Cs activity progressively decreased with depth in the core collected from the other ridge (I). Both profiles from the furrows (J and K) situated on the lower slope showed a peak at a depth of 10 to 20 cm and a decreasing ^{137}Cs concentration in the soil both above and below this peak. The zones of peak activity at different depths probably reflect the position of a former surface or the deposition of soil material which was eroded from upslope by runoff resulting from heavy rain events. Overall, the shapes of the ^{137}Cs depth profiles are consistent with observations made at uncultivated and cultivated sites located in different parts of the world (Zapata, 2002; Mabit et al., 2008).

The inventories of three of the profiles located on the upper slope of the cultivated site (Fig. 2D, F and G) were 15–27% lower than the inventory of the reference site. This can be interpreted as reflecting the removal of soil by erosion processes. In contrast, the ^{137}Cs inventories for two of the core samples collected at the bottom end of the cultivated field (Fig. 2H and I) were 2–41% higher than the reference inventory indicating that these sampling points had experienced deposition.

3.2. The spatial variation of ^{137}Cs

For the undisturbed reference site, the ^{137}Cs inventory determined from the randomly collected soil cores (n = 12) ranged from 403 to 840 Bq m^{-2}. The average value of 568 ± 138 Bq m^{-2} was used to represent the local ^{137}Cs reference inventory. The variation of the values for the individual cores (coefficient of variation (CV) = 24%, n = 12) was within the range reported for undisturbed reference sites by Sutherland (1996). The observed variability is likely to reflect sampling variability, measurement precision and the heterogeneity of the undisturbed soils caused by variation in bulk density, the presence of macro pores and the effects of bioturbation (Owens and Walling, 1996). The activity of soil fauna, such as earthworms, ants and termites, is very high in the tropics (Junge, 2004) and might have led to the redistribution of ^{137}Cs within the topsoil (Mueller-Lemans and van Dorp, 1996; Tyler et al., 2001).

A comparison of the reference inventory documented for the study area at Ibadan with those reported for other studies conducted in other African countries showed that the former was only about one-fifth or a quarter of that reported for northern Morocco (Nakhla watershed, 2655 Bq m^{-2}, Bouhlassa et al., 2000) or Ethiopia (2026 Bq m^{-2}, Argaw et al., 2004) but about twice that reported for a location in southern Zambia (Kaleya catchment, 202 Bq m^{-2}, Collins et al., 2001). These differences reflect the global variability of ^{137}Cs fallout (Sutherland, 1996), with the highest fallout occuring in the northern hemisphere (Aoyama et al., 2006) and smaller fallout in equatorial areas (Owens and Walling, 1996). In addition to this latitudinal zonation, areas of high fallout commonly correspond with areas of high annual rainfall. The ^{137}Cs inventories reported for different sites in West Africa also evidence appreciable variation. The reference values measured in Southwest Nigeria were lower than in Ejura, 100 km Northeast of Kumasi, Ghana, where Antwi (2006) reported inventories of 668 and 1045 Bq m^{-2}. They were also lower than the value of 2066 Bq m^{-2} reported for Southwest Niger (50 km East of Niamey) by Chappell et al. (1998). This variability is probably influenced by the harmattan, a dry and dusty trade wind which blows south from the Sahara into the Gulf of Guinea between December and February. Stoorvogel et al. (1997) recorded a gradient of dust deposition from the arid to the humid zones, which probably also

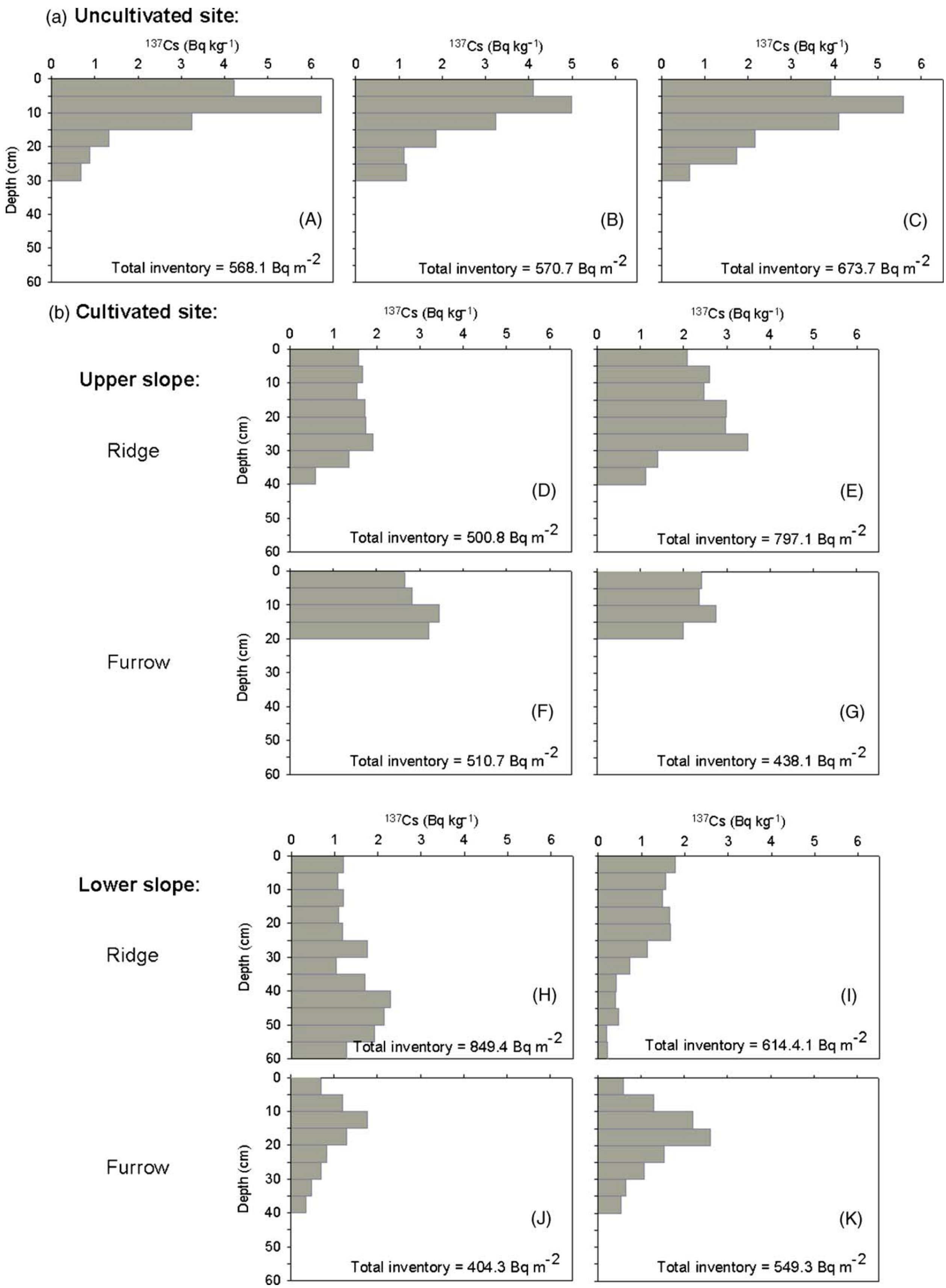

Fig. 2. Depth distribution profiles of ^{137}Cs from the uncultivated (A–C) and the cutlivated sites (D–G).

Table 2
Inventories of all sampling points located in the cultiveted site (us = upper slope, ms = middle slope, ls = lower slope, *x* = mean, SD = (S)standard (D)deviation, min = minimum, max = maximum).

Part of slope	Ridge 1		Furrow 1		Ridge 2		Furrow 2	
	Sampling point	^{137}Cs (Bq m^{-2})	Sampling point	^{137}Cs (Bq m^{-2})	Sampling point	^{137}Cs (Bq m^{-2})	Sampling point	^{137}Cs (Bq m^{-2})
us	1	491.3	12	151.1	23	1494.4	34	271.1
us	2	401.3	13	146.1	24	730.4	35	179.1
us	3	521.4	14	158.4	25	412.8	36	96.9
us	4	628.4	15	294.9	26	537.4	37	247.1
us	5	443.5	16	187.8	27	784.6	38	272.3
ms	6	538.5	17	220.0	28	824.7	39	397.0
ms	7	629.3	18	370.4	29	565.7	40	450.0
ms	8	580.3	19	334.7	30	679.1	41	519.0
ls	9	708.7	20	345.7	31	750.3	42	395.1
ls	10	710.5	21	353.6	32	511.5	43	327.5
ls	11	1191.0	22	670.4	33	627.2	44	684.7
x		622.2		293.9		719.9		349.1
SD		213.5		152.6		286.6		164.8
min		401.3		146.1		412.8		96.9
max		1191.0		670.4		1494.4		684.7

influences the dry deposition of ^{137}Cs (Chappell et al., 1998) and hence, may explain the high ^{137}Cs inventory measured in Niger and the smaller values reported for southern Nigeria.

The ^{137}Cs inventories measured for the 44 individual cores collected from the cultivated cassava field ranged from 97 to 1494 Bq m^{-2} (Table 2). The inventories of the sampling points on the two ridges (average 622 and 720 Bq m^{-2}, n = 11 each) were higher and the inventories in both furrows (average 294 and 349 Bq m^{-2}, n = 11 each) were lower than the ^{137}Cs reference inventory. The different inventories associated with the ridges and furrows reflect the effects of tillage operations resulting in the accumulation of soil containing ^{137}Cs on the ridges and its depletion in the furrows.

A comparison of the average ^{137}Cs values from comparable slope position shows that the ridges on the lower slope (1061 Bq m^{-2}, n = 6) contained about 40–60% more ^{137}Cs that the ridges located on the middle slope (407 Bq m^{-2}, n = 6) and upper slope (645 Bq m^{-2}, n = 10). For the cores taken from the troughs, the difference between the ^{137}Cs values measured were not as great as on the ridges, but the distribution pattern was comparable. This substantial variability of the ^{137}Cs inventories documented for the cultivated field reflected soil redistribution. Areas with reduced ^{137}Cs values relative to the reference inventory indicate the removal of soil material and the movement of soil downslope. Only the ^{137}Cs value of the last position at the bottom of the slope exceeded the reference inventory, demonstrating sediment deposition.

The cross-slope average values for the 11 downslope positions, evidenced less variability and ranged from 297 to 793 Bq m^{-2}, with an overall average of 496 $\pm$ 273 Bq m^{-2} (Table 3). Because the average ^{137}Cs inventory of the upper slope (423 $\pm$ 323 Bq m^{-2}, n = 20) was lower than the average inventory of the middle slope (509 $\pm$ 166 Bq m^{-2}, n = 12) and especially of the lower slope (606 $\pm$ 245 Bq m^{-2}, n = 12), these values were seen to reflect the redistribution of soil material within the field and, more particularly, the removal of soil by erosion from the upper and middle portions and most of the lower portion of the slope. The average ^{137}Cs inventory on the cassava field was 13% lower than the reference inventory, providing clear evidence of soil export from the study field.

The CV of the values differed according to the slope position: A CV of 35% was estimated for the upper slope, 16% for the middle slope, and 33% for the lower slope. Loughran et al. (2002) also encountered similar variation linked to slope position.

3.3. Estimation of soil redistribution rates along the transects

The average soil redistribution rates for the different slope positions in the cassava field are presented in Table 3. The results showed that soil loss occurred on the upper, middle and lower slope, whereas deposition took place only at the base of the lower slope. For example, erosion rates of 54.9 and 9.6 t ha^{-1} year^{-1} were estimated for a positions near the top and the middle of the field, respectively, and a deposition rate of 39.4 t ha^{-1} year^{-1} was determined for the sampling points located at the bottom of the

Table 3
Average rates of soil erosion (negative value) and deposition (positive value) over the last several decades estimated by using the Improved Mass Balance Model (MBM2) (us = upper slope, ms = middle slope, ls = lower slope, *x* = mean, SD = (S)standard (D)deviation, min = minimum, max = maximum, n.e. = not estimated due to program error).

Part of slope	Slope position	Sampling point	Average ^{137}Cs inventory (Bq m^{-2})	Average soil redistribution rate (t ha^{-1} year^{-1})
us	1	1, 12, 23, 34	602.0	n.e.
	2	2, 13, 24, 35	364.2	−37.0
	3	3, 14, 25, 36	297.4	−54.9
	4	4, 15, 26, 37	426.9	−23.4
	5	5, 16, 27, 38	422.1	−24.4
ms	6	6, 17, 28, 39	495.1	−11.1
	7	7, 18, 29, 40	503.9	−9.6
	8	8, 19, 30, 41	528.3	−5.8
ls	9	9, 20, 31, 42	550.0	−2.6
	10	10, 21, 32, 43	475.8	−14.3
	11	11, 22, 33, 44	793.3	39.4
x			496.3	−14.4
SD			130.8	24.7
min			297.4	−54.9
max			793.3	39.4

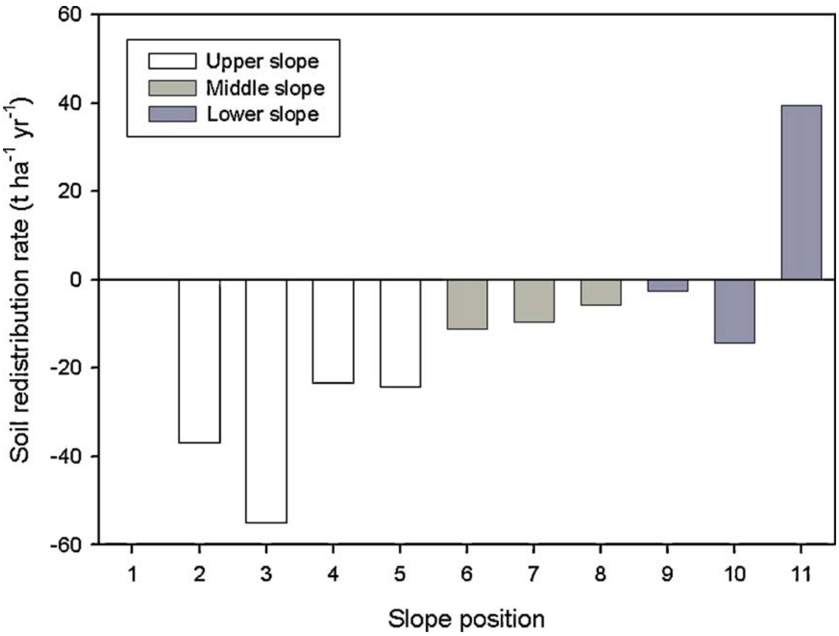

Fig. 3. Average soil redistribution rates for the different slope positions in the cropped field estimated by using MBM2.

slope (Fig. 3). In general, the rates of soil loss progressively decreased downslope probably as a result of the progressively decreasing slope gradient in this direction.

As no correction for particle size has been applied in estimating the soil redistribution rates, this may possibly result in overestimation of erosion rates and underestimation of deposition rates. It is well known that the ^{137}Cs inventory of fine particles is greater than that of coarser particles, due to their increased surface area (Wallbrink et al., 1999; He and Walling, 1997) and that erosion involve preferential removal of fines, whereas deposition is associated with selective deposition of coarser particles.

The gross erosion rate for the cultivated site is estimated to be -18.3 t ha^{-1} year^{-1} and the net soil loss -14.4 t ha^{-1} year^{-1}. Based on the ratio of the net output to the gross erosion rate, a high sediment delivery ratio (SDR) of 78% was calculated. The relatively high rate of soil loss documented for the study field reflects the influence of several factors. One of these factors is the rainfall erosivity which is very high in Southwest Nigeria. Both large and small rainfall events are capable of causing soil erosion at the site, because of the large raindrop size, the high rainfall intensity and the resulting high kinetic energy and erosivity (Salako, 2006). Erosive events are most frequent at the beginning of the rainy season. At this time, the soil surface is still bare as residues from the previous crops are usually burnt or removed and the soil prepared for sowing or planting the ensuing crops after the moisture content of the soil has been increased. Tillage operations are undertaken parallel to the slope gradient to improve drainage and result in a ridge-and-furrow-system which also increases soil redistribution down the slope. The furrows increase the erosion potential, of surface runoff, because the water flow is concentrated in the furrows and the velocity of the runoff is high, which facilitates the downslope transport of soil material (Morgan, 1995). Furthermore, the presence of the ridges and furrows causes a local increase in slope gradient on the side of the furrow, relative to the natural slope, which will increase rates of interrill erosion. Govers et al. (1999) and Kimaro et al. (2005) also emphasized the significance of tillage translocation on within-field soil redistribution and the contribution of tillage erosion to soil redistribution within the study site must also be recognised.

Cassava is planted by placing pieces of stem into the topsoil of the ridges at the beginning of the rainy season. Field observations made in 2006 and 2007 have shown that the growth of the root and tuber is generally slow and that the aboveground parts of the plant do not provide any effective protection of the soil surface during the ensuing wet period (Junge, unpubl.). Hence, the impact of raindrops on the soil surface of cassava fields is high resulting in the destruction of soil aggregates and the removal of the soil particles (Salako et al., 1999).

3.4. Comparison of the estimated erosion rate with measurements of runoff plots

The rates of soil loss estimated from the ^{137}Cs measurements undertaken on the cores collected from the study site were compared with data from measurements of soil loss carried out using traditional erosion plots established on the IITA-campus in Ibadan. Because assessments of soil erosion for cassava fields are rare, records from studies with bare fallow and other crops cultivated on fields with comparable soil texture and slope gradient were also included in this comparison (Fig. 4).

The net erosion rate estimated using ^{137}Cs documented by the authors' study (14.4 t ha^{-1} year^{-1}) was considerably lower than measured rates of soil loss from large plots (max. 0.8 ha, 5% slope gradient) under bare fallow (43.2–157.2 t ha^{-1} year^{-1}) (Lal, 1976). The comparison also showed that the soil loss rate was lower than from large-scale plots where conventional tillage was performed after clearing and cassava and maize were planted in rotation (24 t ha^{-1} year^{-1}) (Lal, 1983), but much higher than soil loss reported for small-scale plots cultivated with different crops. For example, Kirchhof and Salako (2000) reported a soil loss of only 2.8 t ha^{-1} year^{-1} from small plots (80 m^2) cropped with maize in 2006. However, it is difficult to compare the results obtained using different approaches. Small runoff plots in particular are unable to replicate the conditions associated with longer natural slopes, where runoff depths and velocities, and therefore erosion potential, can increase with increasing slope length. Furthermore, tillage operations, including the use of tractors or oxen are problematic to perform on small plots (Hudson, 1993) and the impact of tillage translocation on soil redistribution is therefore reduced.

In general, the results obtained using ^{137}Cs measurements for entire fields or landscape units are likely to be more realistic than

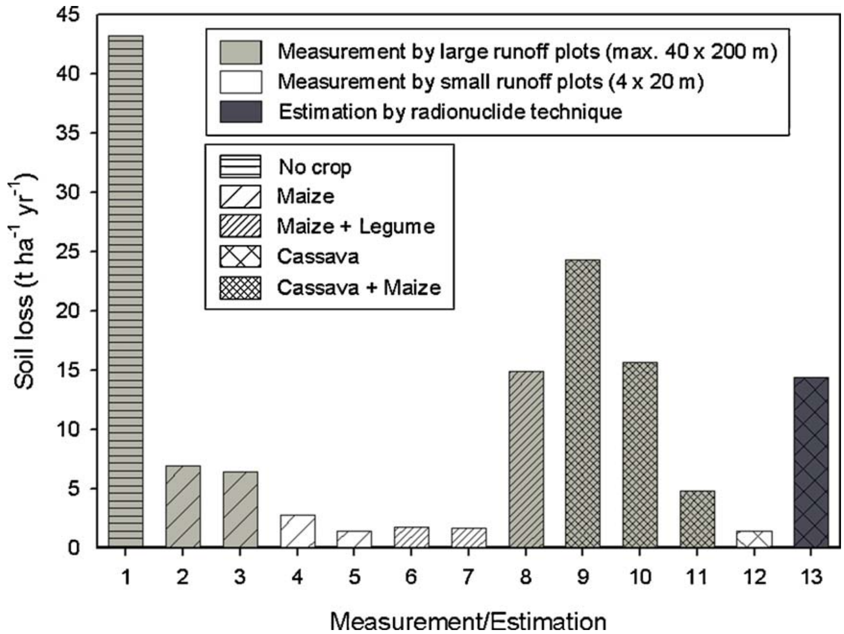

Fig. 4. Soil loss rates (t ha^{-1} $year^{-1}$) measured or estimated in Ibadan by using different techniques. (1) Lal (1976), (2) Kirchhof and Salako (2000), (3) Lal (1984), (4) Lal (1976), (5) Junge (unpubl.), (6 + 7) Kirchhof and Salako (2000), (8) Lal (1995), (9)–(11) Lal (1983), (12) Junge (unpubl.), (13) present study.

estimates based on extrapolation of data obtained from erosion plots. Such plots only measure the soil loss collected at the base or outlet of the plot and cannot provide information on deposition and soil redistribution *within* the bordered plot. Since cores for ^{137}Cs measurement can be collected from the natural landscape, they provide estimates of soil redistribution rates under real conditions. As indicated above, the use of fallout radionuclides to document soil redistribution can provide data on deposition and thus both gross and net soil loss, unlike runoff plot measurements which only provide data on net soil loss from the area of the plot (Zapata, 2002). However, the use of fallout radionuclides in Southwest Nigeria to estimate soil redistribution rates also faces a number of constraints. The availability of appropriate reference sites covered by perennial grass or low herb cover is generally limited, since the land is intensively used and most areas, except for forests, will have been used for cropping within the last 40–50 years. The study also emphasises the limitations imposed by the relatively low ^{137}Cs inventories found in Southwest Nigeria compared to inventories from northern Africa or Europe. These cause a need for greater count time in order to obtain acceptable measurement precision (Zapata, 2002). As suggested by Mabit et al. (2008), the use of ^{210}Pb as an alternative soil tracer to ^{137}Cs could provide a means of addressing this problem in areas where ^{137}Cs inventories are too low to permit precise measurements.

3.5. Soil conservation measures for the derived savanna

The control of water and tillage erosion is imperative for enhancing soil conservation on steepland in the forest-savanna transition zone of Nigeria. Tillage across the slope is a simple approach to erosion control in areas with a low slope gradient. But this technology is not sufficient to control runoff and soil loss on steep slopes or in areas with high rainfall erosivity since contour ridges are easily destroyed by concentrated surface runoff (Lal, 1995). On steeper slopes, alley cropping can be a complementary soil conservation measure. The hedges encourage sedimentation and facilitate the formation of natural terraces (Dercon et al., 2006). However, this measure is less attractive for farmers since it is labour-intensive and can introduce competition for water and nutrients between vegetative barriers and crops (Hauser et al., 2006).

Soil loss can also be prevented or reduced by appropriate crop management. Cover crops, such as *M. pruriens*, can prevent raindrops from detaching soil particles (Lal, 1995). But their cultivation is limited since the farmers are afraid of decreased food crop yields due to competition for water and nutrients (Junge et al., 2008, 2009). Ekboir et al. (2002) and Giller et al. (2009) report a clear benefit of conservation agriculture with regard to erosion control, since mulch reduces the impact of rain drops. This measure is probably worthy of being promoted more strongly in West Africa. However, the use of pesticides for the control of weed and diseases has increased since the beginning of no-till dissemination in Ghana (Ekboir et al., 2002). This might have negative impact on the health of both farmers and the environment, if such products are applied incorrectly (Steiner and Twomlow, 2003).

4. Conclusions

The ^{137}Cs technique for assessing rates and patterns of soil redistribution at the field scale has been successfully applied in a small agricultural field used for growing cassava in Ibadan, Nigeria. The following findings were obtained:

- The ^{137}Cs inventory of the reference site (568 Bq m^{-2}; CV = 24%) was lower than the values obtained from other studies in West Africa;
- The ridges on the cultivated site showed a higher ^{137}Cs inventory than the furrows resulting from the redistribution of soil by the tillage operations. The mean ^{137}Cs inventory associated with cores collected from both ridhes and furrows at a particular position on the slope was used to estimate the soil redistribiution rate at that position on the slope.
- The ^{137}Cs inventories of the cultivated site tended to increase downslope and provided evidence of downslope movement of soil mobilised by erosion processes;
- Use of the MBM2 conversion model indicated that the annual net soil loss from the study site over the last few decades was 14.4 t ha^{-1} $year^{-1}$;
- The soil erosion rates estimated using the ^{137}Cs technique are comparable to those obtained by studies using large erosion plots cultivated with cassava and maize;

- The results obtained from the ^{137}Cs measurements are more meaningful than those provided by small bounded plots, since they reflected both water erosion and tillage-induced soil redistribution.

It is therefore suggested that the use of ^{137}Cs measurements represents a valuable alternative to conventional methods for obtaining quantitative data on soil erosion and deposition which are required to provide a basis for ensuring the sustainable management of natural resources in West Africa.

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